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PHYSICAL EFFECTS OF VEHICULAR DISTURBANCES ON ARID LANDSCAPES.(U)

FEB 81 B HALLET, R M IVERSON, B S HINCKLEY

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Rain simulation experiments conducted in the western Mojave Desert, California, indicate that the use of off-road vehicles on arid lands increases the amount and frequency of water runoff and sheet-wash erosion. Detailed experiments with controlled motorcycle traffic over a loamy sand typical of this region, reveal that these responses are due to a decrease in soil porosity, infiltration capacity, effectiveness of surface stabilizers and hydraulic resistance to overland flow. These effects, which can result even under low vehicle use, tend to be long lived, particularly in arid areas where the slow rates of soil formation render soil loss practically irreversible on a human time scale. Our results suggest that increases in pluvial erosion following ORV use on most slopes are inevitable, but that the magnitudes of those increases are least in areas of low-intensity and duration rains, high natural infiltration rate, low slope and abundant surface sand and gravel. Thus, adverse effects can be minimized by restricting vehicular use to those areas that are naturally least vulnerable or to those that have already been impacted. Moreover, impact can be decreased by avoiding vehicular use where the soil is most susceptible to compaction and structural disruption, as when the soil moisture content is relatively high.

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## REPORT

Arid lands in the southwestern United States are being used increasingly for recreation, housing, and purposes of national defense (1). Thus it is desirable to document, analyze, and, ideally, predict the environmental impacts resulting from such uses. Among the most conspicuous of these impacts is the physical response of desert landscapes to off-road vehicles (ORV's) (2). Evaluation of this response can lead to better understanding of hydrological and geomorphological processes in arid regions and can establish base-line information on substrate responses that affect overall desert ecology.

During the past decade a number of studies have documented the effects of ORV activity on physical and biological components of the desert environment (3). However, because these studies were entirely empirical and often qualitative, their applicability was severely limited to areas characterized by soils and climate practically identical to those at the study site. To remedy this situation, we conducted a quantitative study of ORV impact based on controlled field experiments with special attention directed at the underlying principles. In this report, we summarize our results on the effects of ORV's on soil bulk density and infiltration capacity, and on runoff and erosion processes in the western Mojave Desert, California. We also briefly discuss erosion prediction for disturbed lands, expectations for landscape recovery and implications for land-use planning.

Compaction of soil by vehicle tires may extend to a depth of several decimeters (4-7). This is clearly reflected in the increase in effective soil strength, which is conveniently measured as the resistance to penetration of a metallic cone (Figure 1). We found that soil bulk density increases logarithmically with the number of vehicle passes: to; that is, the largest increase per pass occurs during the first few passes. These results are shown on Figure 2 for a western Mojave Desert loamy sand subjected to 0, 1, 10, 100, and 200 motorcycle passes and having an average moisture content of 6.2 percent (by weight) at the time of compaction. The relevant regression equation

$$\rho = 1.60 + 0.0337 \ln n \quad (1)$$

relates dried bulk density  $\rho$  (tons per cubic meter) of cores, which sample the upper 60 mm of soil, to the number of passes  $n$ , with regression coefficient  $r^2 = .79$ . The form of this empirical equation also appears to be valid for different moisture contents and soil textures (5).

Compaction almost invariably reduces the infiltration capacity of soil. Changes in bulk density however, do not fully reflect the extent to which soil hydrological properties are modified by vehicle use. The terminal infiltration rate  $f_t$  (millimeters per hour) of the compacted loamy sand, measured after 2 hours of infiltration from double-ring infiltrometers, is

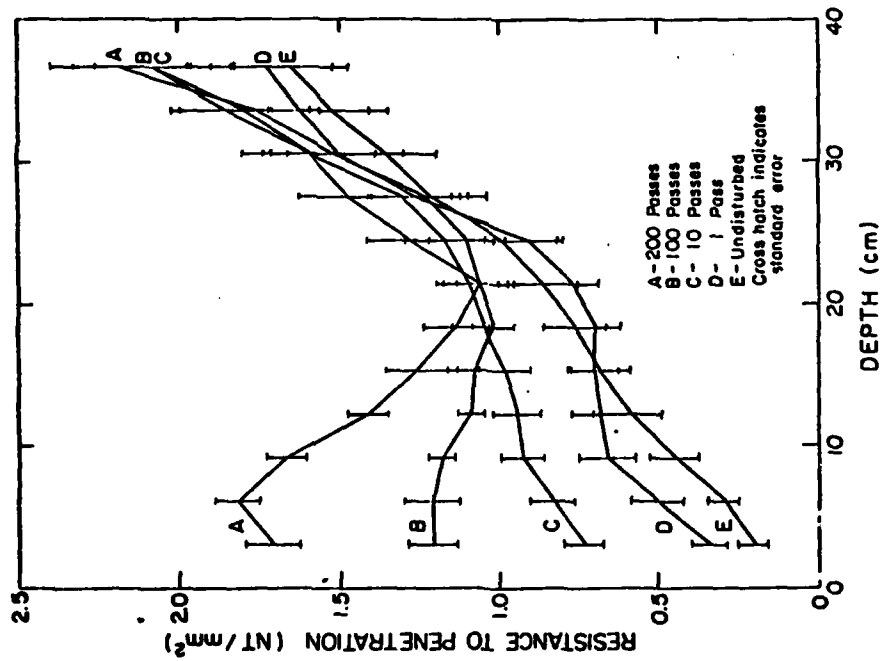


Figure 1. Penetration resistance profiles for the vehicle trails at the Fremont Peak study site. The standard error was calculated as the standard deviation divided by the square-root of the number of passes.

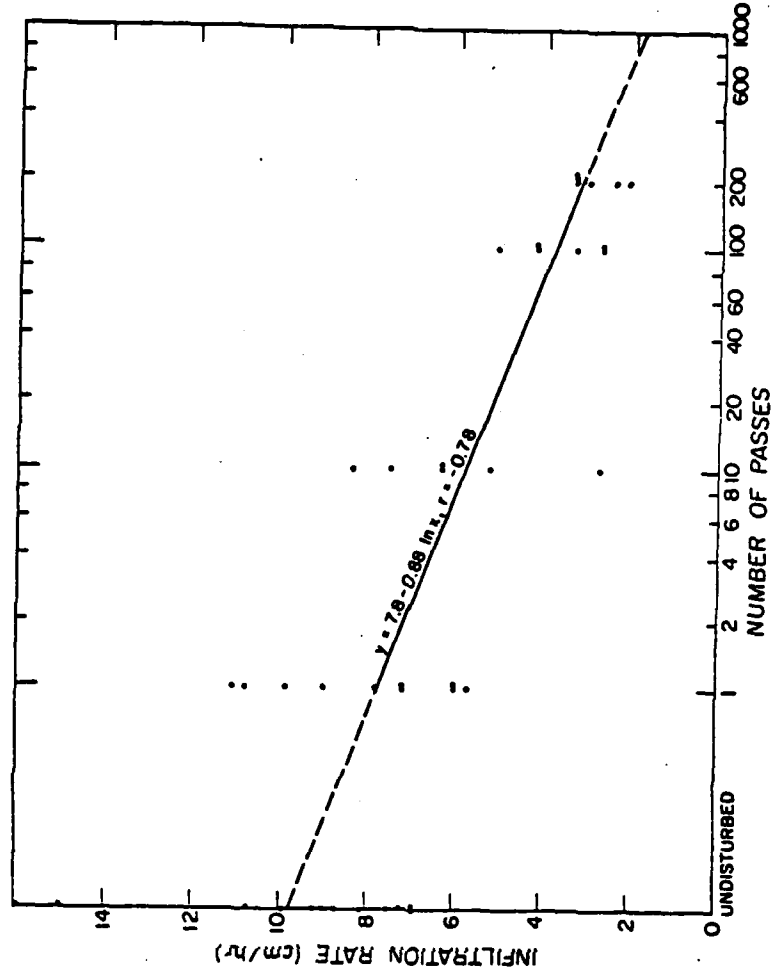


Figure 2. The effects of repeated motorcycle passes on the bulk density in the upper 0 to 6 cm of loamy sand at the Fremont Peak study site. The bulk densities for the undisturbed soil were not included in the regression analysis.

shown in Figure 3 and expressed by

$$f_t = 81 - 9.7 \ln n \quad (2)$$

with  $r^2 = .67$ . Changes in moisture retention characteristics were analyzed in a laboratory pressure-plate apparatus. The samples analyzed were 40 minimally disturbed core samples, 57 mm in diameter by 30 mm in height, taken after various intensities of vehicle use (5). On the basis of these changes, effective pore-size distributions of soils subjected to 0, 1, 10, 100, and 200 motorcycle passes were calculated (8). It is evident that most of the observed increases in bulk density result from destruction of relatively large pores (effective diameter  $>4.5 \mu\text{m}$ ) (Table 1). Because soil infiltration capacity is predominantly controlled by the presence and interconnection of these large pores, ORV use markedly reduces infiltration.

Under natural conditions, most soil-managed western Mojave Desert surfaces have such high infiltration capacities that there is no runoff except during the most intense storms. Rainfall of 40 to 60 mm/hour for 20 minutes would be required to generate runoff on the initially dry, undisturbed surfaces we examined (9). Comparison with available rainfall data suggests that Horton overland flow and accompanying soil erosion may only recur at intervals of tens of years on many such surfaces (10). In contrast, ORV-impacted areas experience local ponding and runoff during rainfall of less than 10 mm/hour and, hence are subjected to much more frequent erosion by overland flow.

In addition to promoting runoff, tire-soil interactions render the ground surface more susceptible to erosion. Granular desert soil materials generally are easily transported by water and wind, and the stabilizing influence of vegetation, surface crusts, and surface concentrations of coarse particles is often of paramount importance in inhibiting rapid erosion under natural conditions. This stabilizing influence is considerably reduced when the terrain is disrupted by ORV's (11, 12). The change is reflected in accelerated water erosion on ORV-used desert hillslopes, where the denudation rates are commonly 1 to 2 orders of magnitude greater than natural erosion rates (13).

We identified the principal factors affecting this accelerated water erosion by analyzing data from 50 rainfall simulation experiments on adjacent used and unused 1-m<sup>2</sup> plots in three ORV-used areas in the western Mojave (7, 11). Paired *t*-tests applied to paired-plot data show that ORV's increase both volume of surface water runoff and sediment yield at 99.9 percent confidence levels. Runoff was typically about five times greater and sediment yield 10 to 20 times greater on vehicle-used plots than on unused plots.

In addition to decreasing soil infiltration capacity and rendering more material available for entrainment, ORV's significantly modify runoff hydraulic properties. Boundary resistance to overland flow, as expressed by Darcy-Weisback friction factors (14), is reduced an average of 13-fold after intensive ORV use (11). This reflects the smoothing of hillsides by vehicles

Figure 3. The effect of repeated motorcycle passes on the terminal infiltration rate of the Fremont Peak loamy sand. The infiltration rates for the undisturbed soil were not included in the regression analysis.

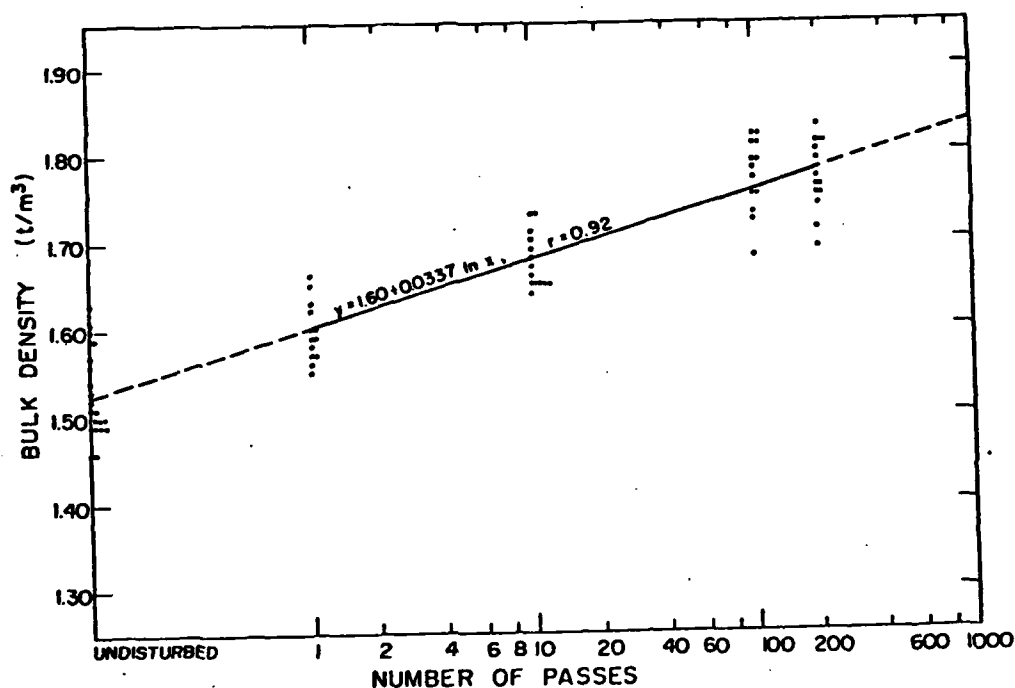


TABLE 1

Changes in soil bulk density and effective pore-size distribution due to compaction by motorcycle passage. The soil, a loamy sand from the western Mojave Desert, was sampled to a depth of 60 mm.

Number of Passes	Mean Bulk Density* (g/cm³)	Pore Volume (cm³/g) in Effective Radii Range		
		$r > 4.5\mu\text{m}$	$1.5 < r < 4.5\mu\text{m}$	$r < 1.5\mu\text{m}$
undisturbed	1.52	.21	.012	.051
1	1.60	.19	.015	.050
10	1.68	.17	.013	.046
100	1.77	.15	.012	.046
200	1.78	.14	.011	.043

\*for 23 samples in the undisturbed area and 12 samples in each trail.



traveling directly upslope. Microtopographic irregularities perpendicular to vehicle trails tend to be subdued, and ruts formed along trails accelerate erosion by channeling runoff and allowing it to propagate more rapidly downhill. Qualitative field observations indicate that intermittent ponding and flow diversions caused by microtopographic roughness—often created by plants and burrowing animals on natural desert hillslopes—are efficient dissipators of flow energy and commonly cause deposition of sediment at short (<1-m) intervals. After ORV use, not only is more runoff power (15) usually available to transport sediment, but greater sediment yields usually result for equivalent amounts of runoff power (Fig. 4). This probably reflects an artificially induced change from water erosion limited by surface stabilization to erosion limited by the sediment transport capacity of runoff. Thus, ORV modifications of the desert surface fundamentally change its response to runoff.

We tentatively identified the areas most susceptible to ORV-induced increases in water erosion by performing multivariate statistical analyses of 22 experimental variables reflecting rainfall and slope characteristics, surface and subsurface soil textures and strength, and infiltration rates. The character of rainfall is by far the most important factor in predicting the increase in erosion. Multiple linear regression relating rainfall energy-intensity (16), slope inclination, and the proportion of the surface covered with fine particles (<1-mm sieve diameter) on undisturbed plots to the increase in sediment yield after ORV use produces a multiple  $r^2$  of .72. Alternatively, rainfall energy-intensity and undisturbed plot infiltration capacity can be used to predict increases in sediment yield ( $r^2 = .83$ ). Overall, the analysis predicts that after ORV use, accelerated water erosion will be least severe in (i) areas subject to rainfall of short duration and low intensity, (ii) areas with high initial infiltration rates and low slope, and (iii) areas with abundant surface sand and gravel (7). However, many of these areas seem to be particularly susceptible to accelerated wind erosion after ORV use (12).

A key concern regarding desert terrain is its rate of recovery after these hydrologic and geomorphic disturbances. Extrapolation of data reflecting 51 years of natural recovery from soil compaction at the abandoned Wahmonie townsite in southern Nevada suggests that roughly a century is required for bulk density, strength, and infiltration capacity to be restored. Invading vegetation usually appears in such compacted areas in a few years, but native perennial species are very slow to return (17). Our observations and those of others (18) suggest that surface crusts reform rather rapidly after disruption, often during the first subsequent period of wetting and drying. Reestablishment of well-developed surface stone covers in severely disturbed areas may require hundreds of years (8), while at other sites recovery may require tens of years (19). Due to this generally slow return to natural conditions, enhanced erosion may continue for a long time and, because of the exceedingly slow formation of desert soil, accelerated soil loss may be the most long-lasting and difficult to alleviate of all ORV impacts.

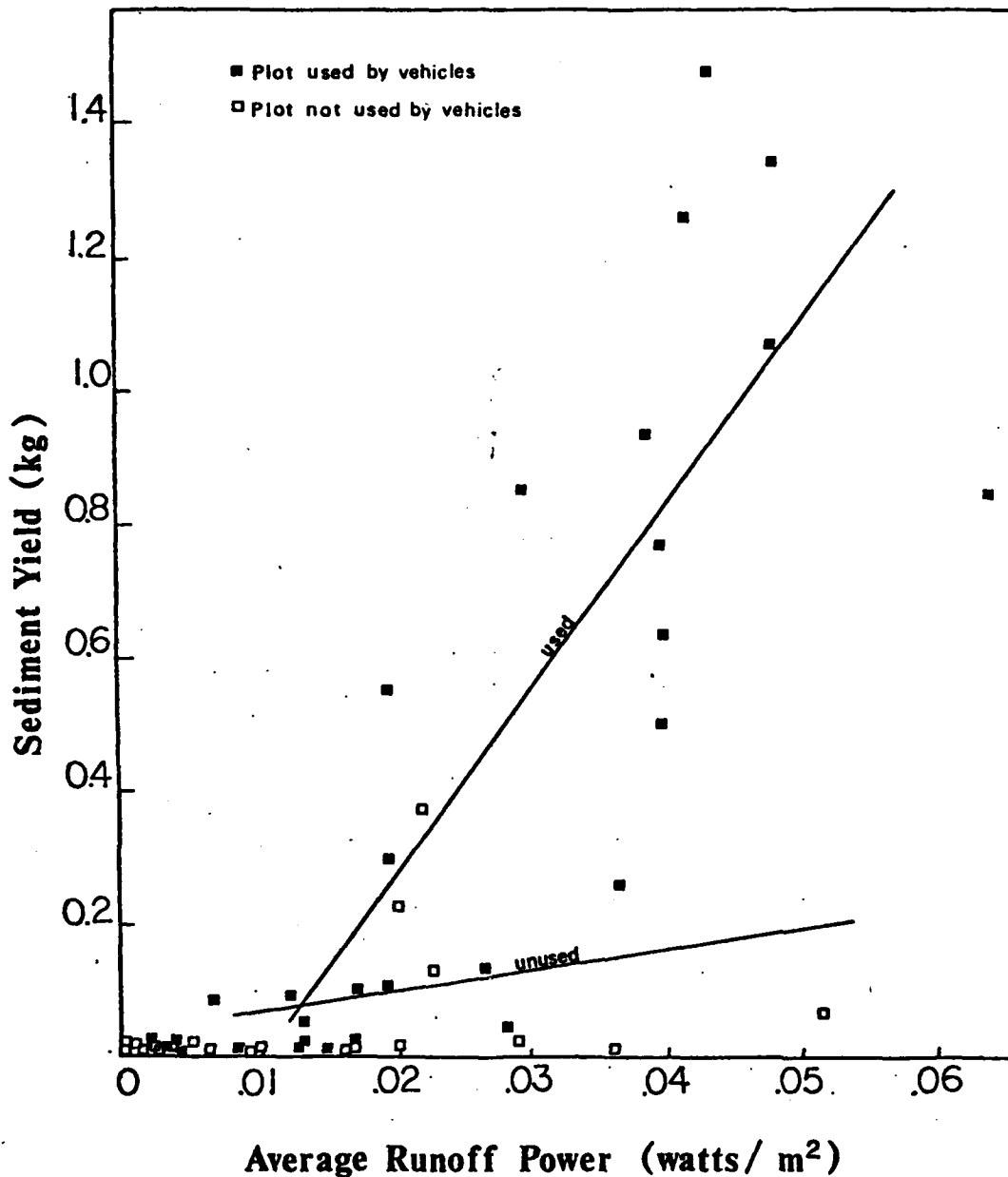


Figure 4. Experimental data and computed regression lines for average runoff power versus sediment yield from 1-m<sup>2</sup> erosion plots used and not used by ORV's (11). These results were derived from 20-minute simulated rainstorms of about 66 mm/hour. Such rainstorms occur on average about once every 100 years in the western Mohave Desert (10). The greater sediment yield (for similar runoff power) from used plots suggests that entrainable grains are more readily available and that transport rates are more directly related to runoff power after use by ORV's.

Analysis of ORV-induced terrain modification leads to findings that hold several implications for desert land-use management: 1) Vehicle use on virtually any but bare rock desert surfaces leads to considerable hydrologic and/or geomorphologic impact even with relatively low levels of use. This suggests that vehicular activities might best be confined to designated "sacrifice" areas in which severe environmental degradation would be spatially restricted. Logical candidates for such areas are those that have already suffered impact, although analysis of precipitation, topographic, and soils characteristics can be used to identify the relative sensitivity of other, initially undisturbed areas. 2) Management of such activity should be conducted at the drainage basin scale. Greatly increased runoff and/or erosion in one part of a basin will affect other parts, and the effects may be very long-lived. 3) Vehicle use should be discouraged during wet periods when all water erosion occurs and when soils are most susceptible to compaction and structural disruption.

We believe that considerable progress has been made towards documenting and understanding the effects of artificial disturbances on arid landscapes. However, we wish to stress that a great deal of work remains in the development of comprehensive scientific criteria applicable to land-use management problems.

#### References and Notes

1. The American Association for the Advancement of Science Committee on Arid Lands [Science 184, 500 (1974)] addressed the impacts of vehicular recreation, and E. Marshall [Science 207, 961 (1980)] described the environmental controversy surrounding construction of the MX missile system on desert lands in Nevada and Utah.
2. D. Sheridan [Off-Road Vehicles on Public Land (Council on Environmental Quality, Washington, D.C., 1979)] reported that 25 percent of Americans participate in ORV recreation.
3. R.H. Webb and H.G. Wilshire, [U.S. Geol. Surv. Open-File Rep. 78-149 (1978)] provide an annotated bibliography of ORV studies.
4. C.T. Snyder, D.G. Frickel, R.F. Hadley, R.F. Miller, U.S. Geol. Surv. Water Res. Invest. 76-99 (1976).
5. R.H. Webb, in preparation. In his book on Stabilized Earth Roads (Elsevier, 1979), A. Kezdi reports general results very similar to those in figure 2.
6. H.G. Wilshire and J.K. Nakata. Calif. Geol. 29. 123 (1976).
7. B.S. Hinckley, in preparation.

8. Effective pore-size distributions were obtained by using the relation  $r = 2\sigma/\psi$ , where  $r$  is maximum effective radius of pores retaining water,  $\sigma$  is surface tension of the air-water interface, and  $\psi$  is matric potential. Matric potential is given as a function of volumetric moisture content by the experimentally determined moisture characteristic curve (5).
9. Rainfall simulation data (7, 11) and drip infiltrometer data (5) at similar localities with predominantly sandy soils yielded similar results.
10. We used U.S. Weather Bur. Tech. Pap. 28 (1958) to estimate the relations between the intensity, duration, and frequency of rainfall in the study areas. Horton overland flow is generated when rainfall intensity exceeds soil infiltration capacity.
11. R.M. Iverson [Earth Surface Processes 5, 369 (1980)] studied processes of accelerated pluvial erosion on desert hillslopes modified by vehicular traffic.
12. D.A. Gillette, J. Adams, A. Endo, D. Smith, R. Kihl (J. Geophys. Res., in press) experimentally studied accelerated wind erosion on desert surfaces used by ORV's.
13. Erosion rates for small drainage basins in semi-arid Wyoming, as measured by R.F. Hadley and S.A. Schumm [U.S. Geol. Surv. Water Supply Pap. 1531-B (1981)], varied from 0.02 to 0.6 mm/year; and point surface lowering measurements from New Mexico by L.B. Leopold, W.W. Emmett and R.M. Mynek (U.S. Geol. Survey Prof. Paper 352-G (1966)) averaged 5.3 mm/year. Compare these values to the 150 mm/year measured by Snyder et al. (4) in Dove Springs Canyon, California, an area subjected to ORV use, or the 220 mm/year measured by R. Stull, S. Shipley, E. Hovanitz, S. Thompson, and K. Hovanitz [Geology 7, 19 (1979)] in Ballinger Canyon, California, another such area.
14. The friction factor is defined as  $f = 8gq(\sin\theta)/v^3$ , where  $g$  is gravitational acceleration,  $q$  is runoff discharge per unit width,  $\theta$  is the inclination of water surface, and  $v$  is mean runoff velocity.
15. Spatially and temporally averaged runoff power per unit area is  $P = \tau_0 v = \rho g q (\sin\theta)$ , where  $\tau_0$  is mean bed shear stress and  $\rho$  is fluid density. R.A. Bagnold [Water Resour. Res. 13, 303 (1977)] discussed the general relation between flow power and sediment transport. M. Kilinc and E. V. Richardson [Colo. State Univ. (Fort Collins) Hydrol. Pap. 63 (1973)] found that the rate of sediment transport by artificially generated shallow flows was closely related to flow power. See also (11).
16. Energy-intensity for these experiments is equal to the average intensity of the rainfall during 20 minutes multiplied by the total kinetic energy released.

17. R.H. Webb and H.G. Wilshire (J. Arid Environ., in press) determined soil property and vegetation recovery rates through measurements of areas undisturbed for known times since their initial disturbance. The Wahmonie site offers this unique opportunity because it is located on the Nevada Military Test Site, which is closed to the public.
18. R.E. Eckert, M.K. Wood, W.H. Blackburn, F.F. Peterson [J. Range Manage. 32, 394 (1979)] studied the effects of crust development on infiltration and the production of suspended sediment on ORV-modified desert soils. P. Farres [Earth Surf. Processes 3, 243 (1978)] experimentally demonstrated that a considerable surface crust may form during a single rainfall.
19. D. Sharon, Z. Geomorphol. 6, 129 (1962).

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- 2) "Processes of Accelerated Pluvial Erosion on Desert Hillslopes Modified by Vehicular Traffic" R.M. Iverson. Earth Surface Processes, Vol. 5, No. 4, p. 369-388, 1980.

Abstracts

- 3) "Accelerated Pluvial Erosion on Desert Hillslopes Modified by Vehicular Traffic" R.M. Iverson, B.S. Hinckley. Ann. Mtgs. Geol. Soc. Amer. 1979, Abstracts with Programs, p. 449.
- 4) "Soil and Vegetation Recovery in a Nevada Ghost Town" R.H. Webb, H.G. Wilshire. Ann. Mtgs. Geol. Soc. Amer., 1979. Abstracts with Programs
- 5) "Compaction of Soil Under Vehicle Traffic" R.H. Webb. Amer. Assn. Advancement of Sci., Pacific Division, Abstracts, Annual Mtg. 1980 p. 50.
- 6) "Effect of ORV-induced Compaction on Infiltration Rates" R.H. Webb. Amer. Assn. Advancement of Sci., Pacific Division, Abstracts, Annual Mtg. 1980 p. 50.
- 7) "Factors Affecting Accelerated Water Erosion on Desert Hillslopes Used by ORVs" R.M. Iverson, B.S. Hinckley. Amer. Assn. Adv. of Sci., Pacific Division, Abstracts, Annual Mtg. 1980 p. 50.

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- 8) "Physical Effects of Vehicular Disturbances on Arid Landscapes" R.M. Iverson, B.S. Hinckley, R.H. Webb, B. Hallet. Science.
- 9) "Recovery of Soils and Vegetation in a Mojave Desert Ghost Town" R.H. Webb, H.G. Wilshire. Journal of Arid Environments.
- 10) "The Effect of Off-road Vehicles on Soil Hydrology and Erosion in the Mojave Desert" R.M. Iverson, B.S. Hinckley, B. Hallet. In The California Desert: An Introduction to Natural Resources and Man's Impact. J. Latting, ed., California Native Plant Society.

A book entitled:

Environmental Effects of Off-Road Vehicles—Impacts and Management in Arid Regions, ed. by H.G. Wilshire and R.H. Webb. Springer-Verlag.

- 11) "General Introduction to ORV Impacts" H.G. Wilshire, R.H. Webb.
- 12) "Common Desert Soil Stabilizers" H.G. Wilshire.
- 13) "Effects of Motorcycle Traffic on Soil Mechanical Properties" R.H. Webb.
- 14) "Effects of Motorcycle Traffic on Soil Hydrologic Properties" R.H. Webb.
- 15) "Accelerated Water Erosion in ORV Areas" B.S. Hinckley, R.M. Iverson, B. Hallet.
- 16) "Historical Disturbances in the Mojave Desert" R.H. Webb, H.G. Wilshire.
- 17) "Recovery of Desert Pavement and Desert Varnish" C.D. Elvidge, R.M. Iverson.

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- 18) "Accelerated Erosion due to Off-road Vehicle Use in an Arid Environment" B.S. Hinckley. Journal of Soil and Water Conservation.
- 19) "Off-road Vehicle Effects on a Desert Soil: I. Controlled Study Results for Motorcycle Traffic" R.H. Webb. Soil Science Soc. of Amer. Journal.

PARTICIPATING SCIENTIFIC PERSONNEL

Principal Investigator: Bernard Hallet, Assistant Professor of Geology and Applied Earth Sciences, Stanford University. (Now Associate Professor of Geological Sciences and Quaternary Research Center, University of Washington.)

Co-principal Investigator: Howard Wilshire, Geologist, United States Geological Survey, Menlo Park, California.

Research Assistants:

Richard M. Iverson, M.S. — September 1979, Department of Applied Earth Sciences

"Processes of Accelerated Pluvial Erosion on Desert Hillslopes Modified by Vehicular Traffic"

Robert H. Webb, M.S. — June 1980, Department of Applied Earth Sciences

"The Effect of Controlled Motorcycle Traffic on a Mojave Desert Soil"

Bern S. Hinckley, M.S. — April 1980, Department of Applied Earth Sciences

"Accelerated Erosion Due to Off-Road Vehicle Use in an Arid Environment"

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